Photovoltaic System Performance Characterization Methodologies

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ABSTRACT

This paper summarizes how a combination of testing, analysis, and modeling methodologies are being used by Sandia to investigate the performance and reliability of photovoltaic systems and their individual components. Topics include modules, arrays, annual energy modeling, and characteristics of off-grid and grid-tied systems.

1. Introduction

The 'performance' of a photovoltaic (PV) power system can be characterized in a variety of ways. Often, systems are recognized and marketed in terms of the power available from the PV array at a standard or reference operating condition. However, understanding the expected energy production by the system is the primary requirement for effectively designing, optimizing, and monitoring system performance. Quantifying expected energy production requires test procedures and modeling tools applied at the cell, module, array, BOS component, and system level. This paper summarizes the applied R&D effort at Sandia to develop and apply test procedures and models that are directly applicable to the needs of system designers, integrators, and owners.

2. Modules

Understanding and optimizing the performance of any photovoltaic system requires test procedures and performance models that quantify the power available from the PV modules for all expected operating conditions. Since the modules are composed of series/parallel combinations of individual solar cells, it is also highly desirable to have a basic understanding of the performance characteristics of the individual cells. In particular the expected open-circuit voltage (Voc) and short-circuit current (Isc), the spectral response, and the temperature coefficient for voltage play a key role in properly interpreting module and array performance measurements.

For over ten years, a concerted effort has been made at Sandia to develop and document outdoor test procedures that quantify the relevant performance characteristics for modules and arrays. Along with these test procedures, has evolved a performance model applicable to modules and arrays of all technologies. The test procedures and model have been improved and validated through collaborative efforts with other organizations [1, 2, 3].

Widespread adoption and application of the Sandia performance model by system integrators, module manufacturers and utilities has occurred. In addition, the performance model has been incorporated in commercially available PV system design software [4]. As a result, Sandia now maintains and continually expands an Access database of performance parameters for over 150 commercial modules [5]. The database provides a combination of Sandia-measured parameters and parameters consistent with the manufacturer's specifications.

3. Arrays

PV arrays are the source of energy for photovoltaic systems, and are composed of series/parallel combinations of individual modules. Analogous to the situation for individual solar cells, performance characteristics obtained from individual modules are instrumental in interpreting the measured performance characteristics of PV arrays. The outdoor module testing procedures developed at Sandia are directly applicable in determining performance parameters for PV arrays, and they have been applied successfully in the field for a variety of PV technologies since 1995 [1,6,7]. For system performance modeling, array performance parameters based on field measurements are desirable because they directly account for array-level affects such as module mismatch and wiring losses.

4. Annual Energy Model

The next step in quantifying system energy production on an hourly, daily, monthly, or annual basis involves coupling the module/array performance model with solar resource and weather information for the site of interest. The National Solar Radiation Data Base (NSRDB) is the most common source for this information for sites in the U.S. [8]. Other databases and solar resource modeling tools such as METEONORM [9] are available for sites outside the U.S. Local measurements of solar irradiance and module temperature can also be used directly in the array performance model to calculate expected performance for a real time comparison with measured performance.

Recently, the Sandia performance model was coupled with NSRDB data to investigate the sensitivity of annual energy production to a variety of factors influencing module performance and system energy production [10]. The dominant factors included module orientation (fixed vs. tracking) and the influence of BOS components. The two least influential factors on system energy production were module mismatch and solar spectral variation.

5. Balance-of-System Components

After achieving a good understanding of the expected energy available from a PV array, the system designer/integrator must recognize that the selection of compatible and reliable BOS components is critical to the performance, reliability, and cost effectiveness of the system. Unfortunately, the research and development effort associated with the BOS components (inverters, charge controllers, batteries, switches, sunlight tolerant wiring, surge suppressors, mounting structures, etc.) in PV systems has lagged the development of commercial PV modules. Without detailed component specifications, the system design tools needed by system integrators have been lacking. In addition, the practice of concurrent design of system components has not yet been routinely practiced by the PV industry. As a result, the performance, reliability, cost, and diversity of application for PV systems have not reached their potential. The following examples illustrate several opportunities for improvement in the performance and reliability of PV systems.

6. Off-Grid Systems

Off-grid (stand-alone) photovoltaic systems provide a significant challenge for systems engineers because of the complexities associated with energy storage and supplementary energy sources (auxiliary generators or wind turbines). Figure 1 schematically illustrates the energy flow and energy losses associated with components in an off-grid system. System integrators are often forced to purchase components from a variety of manufacturers without fully understanding the individual component specifications and the possible incompatibilities between components.

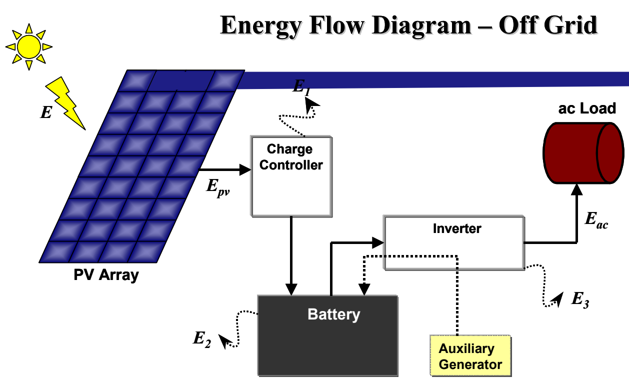

Figure 1. Schematic of energy flow and energy losses in a typical off-grid photovoltaic system.

Evolving techniques for experimentally optimizing the performance, reliability, and safety of off-grid systems were recently documented by Sandia [11]. These techniques coupled array performance testing and modeling with a 30-day system test procedure in order to characterize the performance of individual system components and to quantify the system's expected annual energy production. A primary discovery from this work was that it is not uncommon for off-grid systems to have an overall system efficiency of only about 50%; i.e., only 50% of the energy available from the PV array actually reaches the ac load. With system optimization and continued development of BOS components, overall system efficiency of 75% should be achievable.

Critical design considerations for off-grid systems include: 1) array utilization, as influenced by the combination of charge controller and the array operating voltage established by battery characteristics, 2) parasitic energy consumption, resulting from the strategy for periodic battery overcharge (equalization) and continuous inverter tare loss, 3) 'load control' setpoints (low-voltage disconnect and low-voltage reconnect) in the inverter, which can dramatically influence battery lifetime and stability of system operation, and 4) enclosure designs for electronics and batteries, which should minimize internal temperature variations while adequately venting combustible hydrogen produced by batteries during the charging process.

Figure 2 illustrates an off-grid system that ineffectively uses the energy available from the PV array, i.e., poor 'array utilization.' The scatter-plot of hourly array maximum-power-voltage (Vmp) versus array maximum power (Pmp) was generated using Sandia's array performance model with NSRDB data for Alamosa, CO. The horizontal spread in the data was caused by hourly variation in solar irradiance, and the vertical spread was due primarily to the operating temperature of the array (array's temperature coefficient for voltage). The dashed box in the figure shows the range for array operating voltage (battery voltage) which depends on the battery state-of-charge, which in turn depends on how heavily the system has been exercised by the system user. In this example, it might be common for the battery voltage to be in the range from 24 to 27 V for most of the time during the year, in which case approximately 25% of the energy available from the array will be lost due to poor array utilization. The continued development of advanced charge controllers with a maximum-power-point-tracking (MPPT) capability will have a significant impact on the efficiency of off-grid systems and will allow more flexibility in array design options.

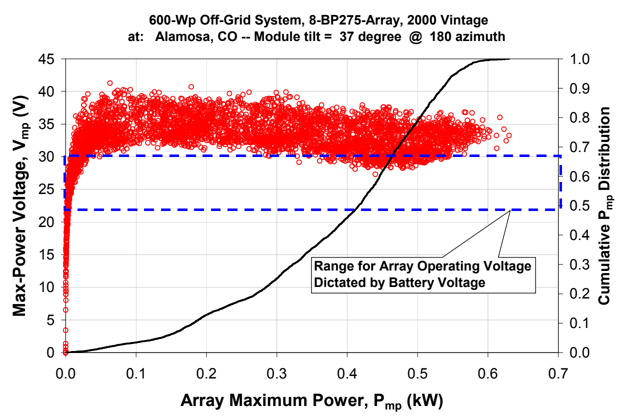

Figure 2. Poor array utilization caused by an array operating voltage (battery voltage) below the array's maximum-power-voltage for most of the year in Alamosa, CO.

7. Grid-Tied Systems

Design optimization for grid-tied PV systems is significantly easier than for off-grid systems because the battery, charge controller, and auxiliary energy sources have been eliminated. Nonetheless, the designer/integrator must pay careful attention to array sizing, inverter performance characteristics, and the long-term reliability of all system components. As for off-grid systems, the combination of array performance modeling and system performance measurements have been used to investigate energy losses and opportunities for improving performance and reliability.

With design optimization and careful installation, a grid-tied system efficiency of 90% should be achievable.

Figure 3 illustrates the calculated array performance characteristics, along with inverter operational constraints, for an example grid-tied system in Albuquerque. The dashed rectangle defines the inverter's MPPT voltage range (250 to 550V) and its upper limit for dc power input from the array (2.7 kW). If the array's maximum-power-voltage is below 250V, the inverter will shut down until it senses an array voltage greater than the start up voltage, in this case 300V. Array voltages greater than 600V may damage the inverter. If the maximum power available from the array exceeds 2.7 kW, then the inverter stops tracking the array's maximum-power-point and goes into a 'power limiting' mode clamped at 2.7 kW.

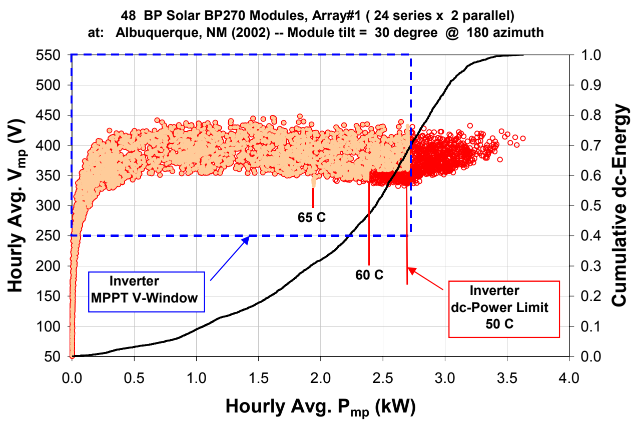

Figure 3. Calculated array performance for grid-tied system in Albuquerque showing operational constraints imposed by inverter performance characteristics.

For the system design illustrated in Figure 3, the array was oversized, and there were many hours during the year when the power available from the array exceeded the input limit for the inverter. In the power-limiting mode, the inverter raises the array operating voltage in order to reduce the power delivered by the array, as illustrated in Figure 4. In the event of high ambient temperature or restricted airflow, the inverter may also protect itself from overheating by lowering its power limit (thermal derate) to the degree necessary to protect electronic components. Figure 3 also shows the extent of thermal derate possible for inverter heat sink temperatures of 50, 60, and 65°C.

In cooperation with manufacturers and other test laboratories, Sandia is also working to improve the performance and reliability of inverters, and to provide the test support required to quantify the inverter performance parameters and operational constraints needed for system design and energy modeling [12].

8. Reliability

The reliability of photovoltaic systems is a crucial factor influencing the future growth of the photovoltaic industry. System reliability includes the reliability of individual components, interactive effects between components, and changes in component behavior with age. Our system characterization efforts also include the determination of module and array performance degradation mechanisms and degradation rates as a result of long-term outdoor exposure [13, 14]. In cooperation with module manufacturers, well-controlled outdoor exposure testing of commercial modules was initiated at Sandia in 1990. The module exposure effort was expanded in 1997 to include a hot/humid environment at the Florida Solar Energy Center (FSEC) in Cocoa, Florida and a hot/dry environment at the Southwest Technology Development Institute in Las Cruces, New Mexico. In collaboration with both module manufacturers and system integrators, field performance tests documenting array performance and degradation rates have also been routinely conducted. Field tests in the last year have been instrumental in identifying unexpected reliability issues in some thin-film module technologies, and in motivating a more proactive research effort focused on thin-film module reliability.

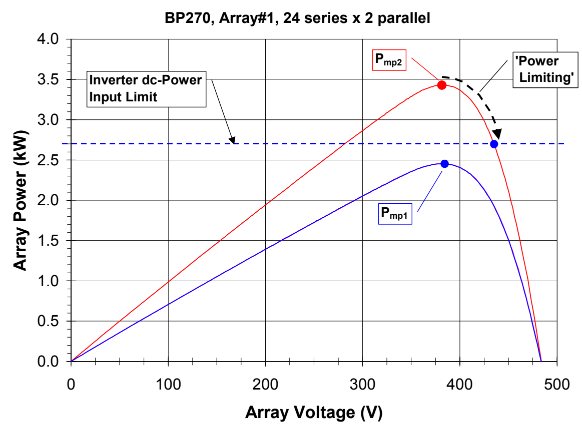

Figure 4. Illustration of the inverter's power limiting procedure when the power available from the array exceeds the input limit for the inverter.

As an example of long-term module exposure testing, Figure 5 shows the normalized power for two commercial amorphous silicon modules of the same type over almost 5 years of continuous outdoor exposure at Sandia. The effects of rapid initial degradation, seasonal (thermal) annealing, and a long-term degradation rate were all evident in the test results. Given the previous discussion concerning selection and matching of arrays with power conditioning components, it is evident that modules with aging characteristics like those shown in Figure 5 make the task of system integration more difficult.

Highly repeatable test and analysis procedures are required to accurately quantify small degradation rates within a reasonable degree of uncertainty. Nonetheless, an accurate determination of typical degradation rates is important to the system integrator and owner, as well as to module manufacturers. We are currently using such procedures to quantify degradation rates in a wide variety of commercial modules after 5 to 12 years of field exposure at Sandia, FSEC, and SWTDI. Module technology types included in this effort include crystalline-Si, multicrystalline-Si, EFG-Si, polycrystalline-Si, amorphous-

Si, and copper-indium-diselenide. It is anticipated that the degradation rates determined will be smaller in magnitude and more defensible than unfavorable results currently being published by a European test lab [15].

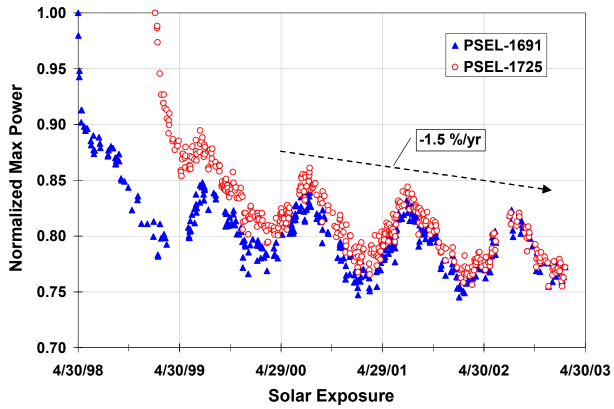

Figure 5. Illustration of the aging characteristics for two commercial amorphous silicon modules over 5-yr period in Albuquerque, New Mexico.

9. Conclusions

A concerted effort is being made to develop and apply the testing and analysis methodologies needed to better understand the performance and reliability of all components associated with off-grid and grid-tied photovoltaic systems. Close cooperation with key members of the photovoltaic industry continues to make this a very active and fruitful effort.

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